CONTINUOUSLY-VARYING, THREE-DIMENSIONAL SU-8 STRUCTURES: FABRICATION OF INCLINED MAGNETIC ACTUATORS

Yoonsu Choi, Kieun Kim, Mark G. Allen

Department of Electrical and Computer Engineering, Georgia Institute of Technology
791 Atlantic Drive, N.W., Microelectronics Research Center, Atlanta, GA 30332
Phone: (404) 894-9905, Fax: (404) 894-2776, Email: yoonsu@go.com

ABSTRACT

A fabrication approach using SU-8 epoxy photoresist to create three-dimensional structures with continuous variation in the third dimension has been developed. Using this approach, a ramp structure 300 μm tall with angle of inclination of 36 degrees has been fabricated. In an extension of the process, both metal and dielectric materials can be deposited and patterned on the inclined surface. The current application for these ramp structures is the fabrication of magnetic switches of well-defined inclination relative to the substrate. Such switches were produced using the ramp structures as an underlying mechanical support. Switch arrays with inclined orientation are able to actuate consistently in the same direction in response to external magnetic fields. Under magnetic actuation, the switch produced a contact resistance of 5.1 Ohms.

INTRODUCTION

A common approach to magnetic microactuation is the use of NiFe permalloy beams or plates interacting with external magnetic fields [1-5]. One challenge is the precise control of the direction of actuation. For example, even if the desired direction of motion is downward toward the substrate, curvature in a permalloy beam can cause the beam to actuate in an undesired direction. Careful alignment must be made between the direction of the magnetic field and the easy axis of the beam such that the torque generated causes the beam to move in the desired direction. To overcome these difficulties at the device level, a microactuator has been created that uses an inclined surface, or a ramp, which slopes downward below the horizontal plane of the anchor points, to ensure a correct direction of actuation over a broad range of external magnetic field orientations. This paper will detail the development of the three-dimensional ramp structure using SU-8 epoxy, and illustrate its utility in a magnetically actuated switch.

PROCESS AND DEVICE CONCEPTS

The process concept relies on the planarization and flow properties of SU-8 epoxy photoresist. As Figure 1a illustrates, in order to take advantage of the flow properties of the SU-8, it is necessary to construct a trough that will serve as a fluidic trap for the SU-8 as it cures into the ramp shape. After this trough is created, the SU-8 is deposited into the area bordered by the three

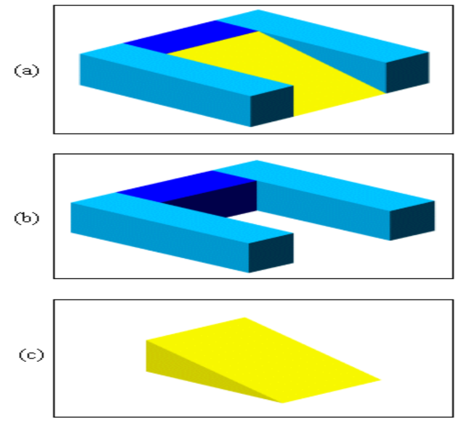


Figure 1: Illustration of continuously varying three-dimensional structure fabrication process concept

walls of the trough. This can be accomplished either by spin casting a thick layer of SU-8 over the entire substrate, or by microdispensing precise quantities of SU-8 specifically into the trough area. Subsequently the substrate is tilted at some desired inclination allowing the SU-8 to settle and planarize parallel to the horizon but inclined relative to the substrate surface, as shown in Figure 1b. The SU-8 is then cured to form the final inclined state. Finally the trough walls are removed to complete the ramp structure, as shown in Figure 1c. Although the primary application explored in this paper is the fabrication of magnetic switches, many alternative uses for continuously-varying, three-dimensional SU-8 structures can also be considered using this process. Such applications include microoptics, microfluidics, and mechanically-interlocking structures.

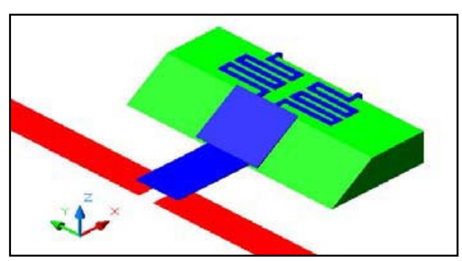


Figure 2: 3D perspective view of inclined microswitch design

Figure 2 shows a 3D model of a magnetically actuated switch that exploits the inclined ramp structure. The underlying incline guarantees that when a near-uniform magnetic field approximately normal to the substrate is

0-7803-7185-2/02/$10.00 ©2002 IEEE

applied, the actuation will unambiguously occur in the downward direction. In the presence of an external magnetic field, a permalloy material will develop a net magnetization $\underline{\mathbf{M}}$. This magnetization, interacting with the applied magnetic field $\underline{\mathbf{H}}$ will cause a net torque on the permalloy material:

$$T_{field} = \underline{\mathbf{M}} \times \underline{\mathbf{H}} = M\,H \sin\alpha$$

where α is the angle between $\underline{\mathbf{M}}$ and $\underline{\mathbf{H}}$. This torque will seek to align the magnetization vector in the same direction as the applied magnetic field. The direction of $\underline{\mathbf{M}}$ will depend both on the easy axis of the material as well as the inclination of the material relative to the external magnetic field [3]. By controlling the angle of inclination, therefore, the direction of the generated torque (e.g., downward) can be unambiguously determined on the device level.

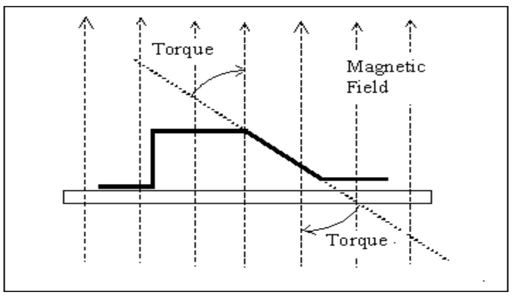
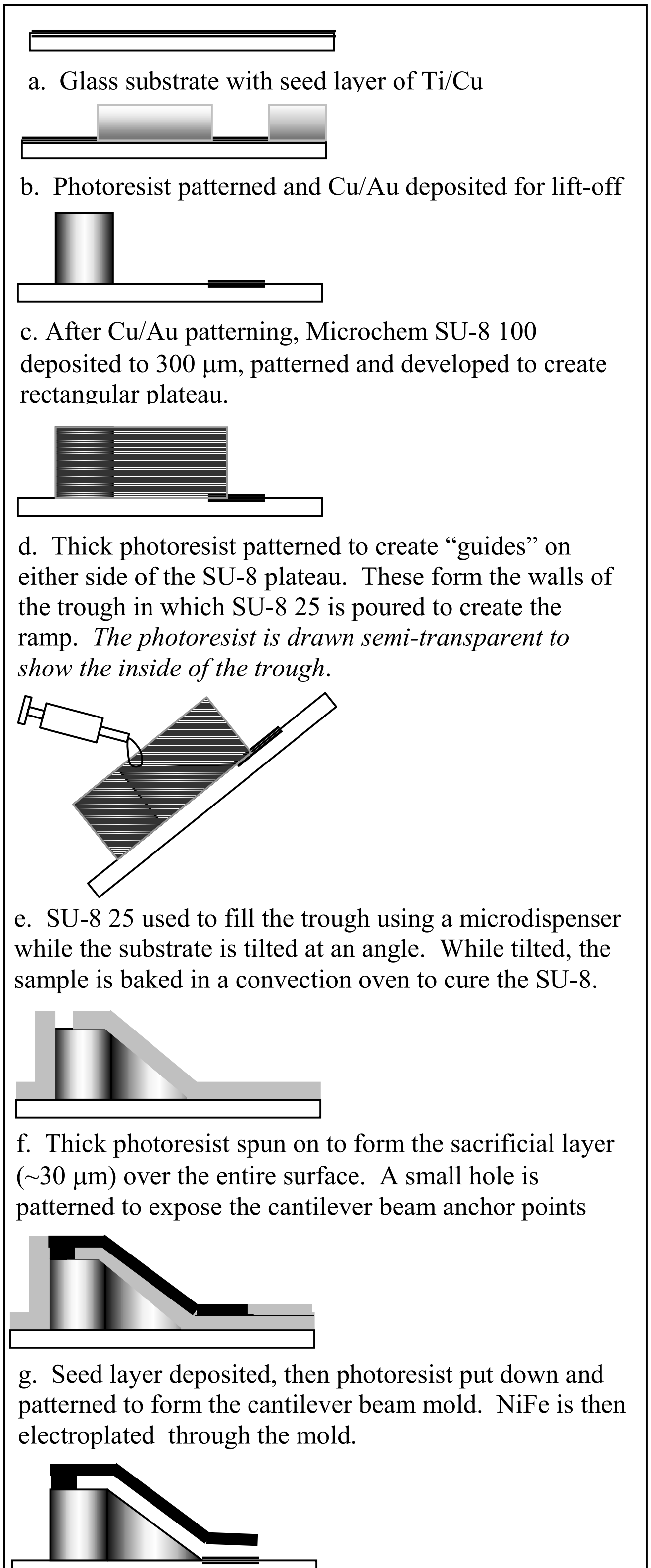


Figure 3: Applied force due to uniform external magnetic field (side view of the switch)

The application of a ramp structure to create an inclined magnetically actuated switch offers several benefits. The first is that a distribution of switches on a sample surface in various X-Y orientations can all be actuated in the same Z-direction by a single field. This could be the case in a reconfiguration application, where a large array of switches should change state by application of a single, global magnetic field. The second is that it is often difficult in practice to generate truly uniform global fields without specialized equipment. In this case, an array of switches actuated by a global field could experience a spatially varying magnetic field with, e.g., the greatest uniformity in the center. A switch with sufficient inclination will be more tolerant of spatial and angular variations in the magnetic field and thus the deflection direction can be better controlled. Finally, an array of switches can be actuated with some of the switches in the array deflected towards the substrate surface and others are away from the substrate surface using a single global magnetic field by the judicious application of the inclinations.

FABRICATION

The fabrication procedure uses surface micromachining techniques of metallization and electroplating, in addition to the use of SU-8 epoxy to create very tall vertical structures critical in developing the inclined ramp. Figure 4 illustrates the fabrication sequence. Initially, a seed layer of Ti/Cu is deposited on an optically flat glass substrate. Photoresist was then spun on the substrate and



a. Glass substrate with seed layer of Ti/Cu

b. Photoresist patterned and Cu/Au deposited for lift-off

c. After Cu/Au patterning, Microchem SU-8 100 deposited to 300 μm, patterned and developed to create rectangular plateau.

d. Thick photoresist patterned to create "guides" on either side of the SU-8 plateau. These form the walls of the trough in which SU-8 25 is poured to create the ramp. *The photoresist is drawn semi-transparent to show the inside of the trough.*

e. SU-8 25 used to fill the trough using a microdispenser while the substrate is tilted at an angle. While tilted, the sample is baked in a convection oven to cure the SU-8.

f. Thick photoresist spun on to form the sacrificial layer (~30 μm) over the entire surface. A small hole is patterned to expose the cantilever beam anchor points

g. Seed layer deposited, then photoresist put down and patterned to form the cantilever beam mold. NiFe is then electroplated through the mold.

8. Top photoresist, seed layer, and sacrificial photoresist layer all removed to release and complete the inclined, magnetically actuated microswitch.

Figure 4: Outline of fabrication process

exposed to create the lower conducting patterns for the switch. The conducting structures were then created via electrodeposition of Cu. Au was then deposited using an electron beam evaporator and patterned on the Cu surfaces by using lift-off and removing the photoresist mold. Next, SU-8 100 epoxy from Microchem, Inc. was spun on to a thickness of 300 μm, and patterned to create a rectangular plateau structure. A thick negative photoresist (Futurex NR9-8000) was then used to create guides along both sides of the plateau. These now formed three sides of a trough in which epoxy was poured to create the ramp. This was done by tilting the substrate itself at an angle of 36 degrees and filling the trough with SU-8 50 epoxy using a microdispenser. The inclined substrate was then put in a convection oven to cure the SU-8 50. Using this method, ramps of different inclination angle can be created by varying the tilt angle of the substrate during the microdispersion and subsequent curing of the epoxy. However, if the SU-8 used is not of sufficiently high viscosity, the ramp upon curing may possess a concave curvature. To minimize this curvature and ensure that the ramp is as flat as possible, multiple microdispersions may be necessary to smooth out the concavity. After curing, the sidewalls of the ramp were photodefined in the SU-8, and the photoresist guides were removed, leaving behind just the ramp and the plateau that had served as its far-wall. At this point, the inclined structure fabrication is completed (Figure 4e). Figure 5 shows a close view of an SU-8 inclined ramp structure.

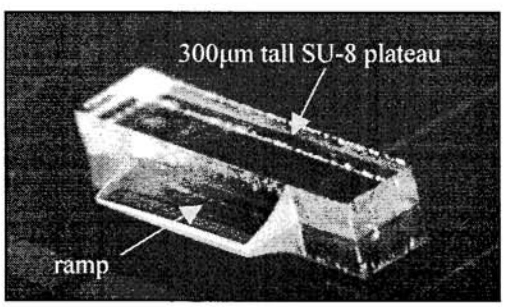


Figure 5: Photomicrograph of inclined SU-8 structure.

To continue with fabrication of magnetic switches, thick positive photoresist (Clariant AZ PLP 100 XT) was spun over the sample surface to act as a sacrificial layer of 30 um thickness. This sacrificial layer PR was patterned to expose areas on the SU-8 plateau upper surface on which the cantilever would be anchored. Next a seed layer of Cu was conformally deposited over the entire surface and a second photoresist layer deposited over this seed layer, which was then patterned to form the mold for the cantilever beam. NiFe was electroplated through this mold to form the beam and the PR and seed layers were removed. Finally, the sacrificial layer was removed to release the switch. Figure 6 shows a close view of a completed inclined microswitch.

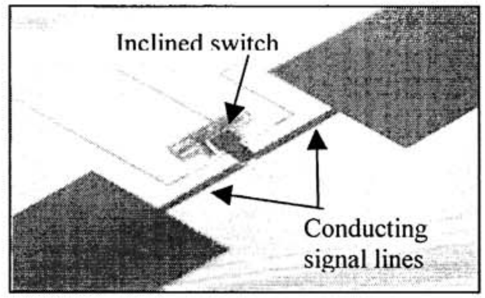


Figure 6: Photomicrograph of completed microswitch built on inclined SU-8.

An extension of the fabrication methodology is to create metal and dielectric structures on the ramp surface for devices where electrostatic forces may be of importance. This was done by adding several steps after the ramp was fabricated. After curing the tilted substrate, a seed layer is conformally deposited and a photoresist layer is spun on the sample and a simple square pattern is created in the resist. The challenge here lies in the fact that the inclined surface creates a continuously-varying airgap between the resist and the mask surface. The airgap may be a source of photolithographic error for more complex structures. However, for the relatively simple rectangular patterns required for the switch application, no serious problems were encountered. After the mold is created from the resist, it is used to electroplate Cu. The resist and the seed layer are removed. Next, PECVD is used to deposit a thin layer (~400 nm) of SiO_2 over the entire surface, after which photoresist is used to pattern this SiO_2 over the electroplated Cu. Figure 7 illustrates the Cu square structure formed on the ramp surface. Figure 8 shows the result after the SiO_2 is deposited and patterned.

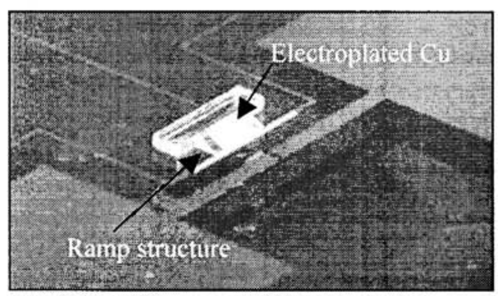


Figure 7: Cu structure electroplated on the ramp surface

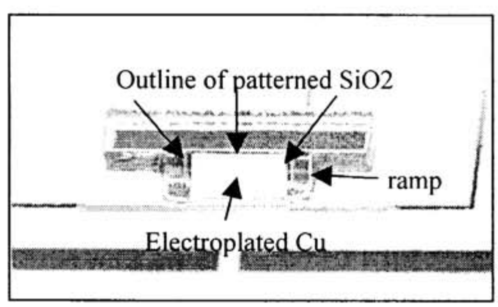


Figure 8: After SiO2 is deposited and patterned on ramp surface

SWITCH RESULTS

The fabricated inclined magnetic switch has been characterized by exposing the switch to various external magnetic fields. Both permanent magnets as well as electromagnetic coils have been used to successfully actuate the device. The functionality of the device as a magnetic switch is demonstrated in Figure 9, showing a switch centered over an external permanent magnet and an illuminated LED controlled by the closed switch. Switch parameters under closed condition were measured and it was found that the inclined structure gave a contact resistance of 0.7 ohm under mechanical actuation. When actuated and held closed with an external magnetic field the contact resistance was 5.1 Ohms. The external magnetic field needed to actuate the switch was measured using a handheld gaussmeter and found to be approximately 120 gauss.

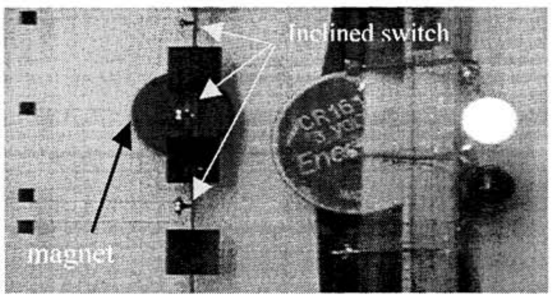


Figure 9: LED activated by magnetically actuated inclined switch using an external magnetic field

CONCLUSION

Continuously-varying epoxy ramp structures have been demonstrated. These structures exploit the flow and planarization properties of SU-8 epoxy resists. To illustrate the utility of these structures, an inclined magnetic switch using the SU-8 ramp structure as an underlying mechanical support was fabricated. Reproducible downward deflection of the cantilever beam was observed over a broad range of external magnetic field orientations. Under mechanical actuation the switch produced 0.7 Ohms of contact resistance and under magnetic actuation produced 5.1 Ohms of contact resistance. In addition, electroformed metal structures and patterned dielectric structured have been successfully fabricated directly on the continuously-varying three-dimensional surface. Although the primary application explored in this paper is the fabrication of magnetic switches, many alternative uses for continuously-varying, three-dimensional SU-8 structures can also be considered using this process. Such applications include microoptics, microfluidics, and mechanically-interlocking structures.

ACKNOWLEDGEMENTS

This project has been sponsored by the Defense Advanced Research Projects Agency (DARPA) under the auspices of the RECAP program. Microfabrication was carried out in the Georgia Tech Microelectronics Research Center with the assistance of the staff. The authors would like to thank Dr. Lon Pringle, Dr. Paul Friedrich, and Mr. Stephen Blaylock of the Georgia Tech Research Institute for valuable technical discussions and assistance.

REFERENCES

[1] William P. Taylor, Oliver Brand, and Mark G. Allen, "Fully Integrated Magnetically Actuated Micromachined Relays," *JMEMS*, Vol. 7, No. 2, June 1998, pp.181-191

[2] John A. Wright, Yu-Chong Tai, and Shih-Chia Chang, "A Large-Force, Fully-Integrated MEMS Magnetic Actuator," *Technical Digest: 1997 International Conference on Solid-State Sensors and Actuators: Transducers '97*, Vol. 2, Chicago, IL, pp. 793-796, June 1997.

[3] Jack W. Judy and Richard. S. Muller, "Magnetic microactuation of torsional polysilicon structures," *International Solid-State Sensor and Actuator Conference Digest of Technical Papers* (Transducers `95), Stockholm, Sweden (June 25-29, 1995), vol. 1, pp. 332-335

[4] C. Liu, Tom Tsao, Y. C. Tai and C. M. Ho, "Surface Micromachined Magnetic Actuators," *Proceedings, 1994 IEEE Micro Electro Mechanical Systems Workshop (MEMS '94),* Oiso, Japan, pp. 57-62, Jan. 25-28 (1994).

[5] Ruan, M., Shen, J., and Wheeler, C., *"Latching Micro Electromagnetic Relays," Solid-State Sensor and Actuator Workshop (Hilton Head 2000),* Hilton Head Island, SC (June 4-8, 2000), pp. 146-149